Cold Atom Quantum Simulators

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The connection between the microscopic description of the interactions between individual components (as specified, for example, by a two-particle interaction Hamiltonian) and the collective macroscopic behavior of multicomponent systems (manifested in collective phenomena such as phase changes) is central to many branches of physics and chemistry. In principle, the collective properties simply result from solving the dynamics of some theoretical model of the microscopic behavior. However, because the complexity of a multicomponent quantum system grows exponentially with the number of degrees of freedom, solving such quantum problems is almost always an intractable problem with any classical device. Perhaps the best hope to understand these systems is to use another multicomponent system over which we have complete control and whose collective characteristics we can measure directly. Such a *quantum simulator* could be used, for example, to predict the behavior of condensed phase systems and potentially impact fields as diverse as condensed matter, quantum field theory, and nuclear physics where numerous intractable models exist. Testing such theoretical models will advance the understanding of the low-energy physics of strongly correlated systems, such as high-T_c superconductors and f-electron materials. In addition, by engineering new states of matter, it is hoped condensed-matter experimentalists will be inspired to search for and investigate analogous new states in real materials.

In Theoretical Division we are developing, in collaboration with experimental groups Biological and Quantum Physics (P-21) and Isotope and Nuclear Chemistry (C-INC), a capability in experimental and theoretical quantum simulation based on trapped ion and neutral atom physics. Our goal is to adapt our existing experiments into quantum simulators in which the complex physics of fundamental quantum models, mainly from condensed-matter physics, can be investigated. Quantum simulators can be thought of as a special type of quantum computer optimized to investigate specific, complex physical problems that classical computation methods do not efficiently solve, thus developing a quantum simulator would be a major step towards a practical quantum computer.

We will use arrays of cold atoms, such as those shown in Fig.1, to simulate real materials. The physics of these systems maps onto equivalent arrays of quantum spins, yet they can be free of complicating impurities and defects, they can be controlled more precisely, and their evolution can be characterized and measured more easily. Atom-laser interactions simulate site-specific potentials, and state-dependent optical forces manipulate atomic positions to simulate spin-spin interactions. To investigate the capabilities of quantum simulators, we already have candidate models, like the bi-linear bi-quadratic Heisenberg model that displays coexistence and competition of unusual magnetic and superfluid states. Other models display novel and complex topological orderings, which are extremely difficult to observe in naturally occurring materials. One of our more challenging tasks is identifying ways to read out the results of a complex simulation using spectroscopic and interferometric techniques that will let us measure the collective properties of our atomic systems. Additionally, the finite temperature of the atoms, fluctuations in laser parameters, and other practical experimental limitations result in errors in the final results of the simulations, that must be assessed.

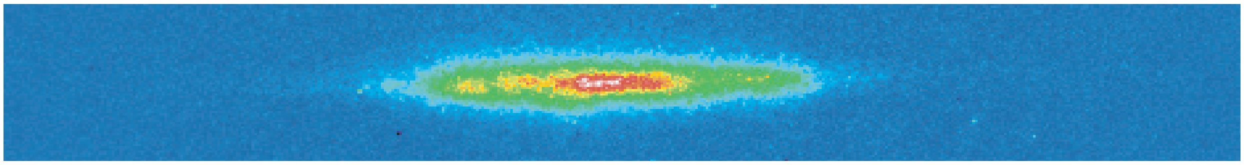

Fig. 1a.

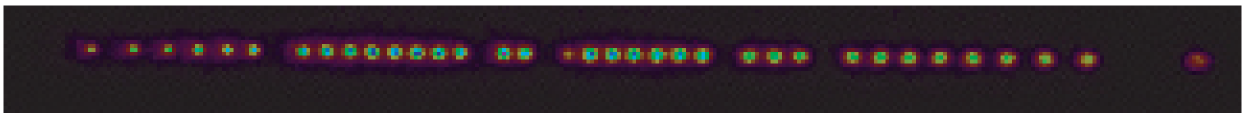

Fig. 1b.

Figure 1—
Quantum Simulation Technologies: (a) a cloud of Rb atoms in the Los Alamos optical lattice (courtesy Xinxin Zhao, C-INC); and (b) a string of $^{88}Sr^{+}$ ions in the Los Alamos ion trap (courtesy Dana Berkeland, P-21).